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Interactions between surface integrity parameters on AISI 304 austenitic stainless steel components by ultrasonic impact treatment

G. Q. Wang [a], M. K. Lei [a,*], D. M. Guo [b]

[a] *Surface Engineering Laboratory, School of Materials Science and Engineering, Dalian University of Technology, Dalian 116024, China*

[b] *Key Laboratory for Precision and Non-traditional Machining of the Ministry of Education, Dalian University of Technology, Dalian 116024, China*

* Corresponding author. Tel.: +86-411-84707255; fax: +86-411-84706192. *E-mail address:* mklei@dlut.edu.cn

Abstract

Surface modification processes are enabling a high performance manufacturing by improving surface integrity with controllable surface integrity parameters, particularly for high performance components demanding a combination of functional properties, such as wear, corrosion and/or anti-fatigue properties etc. Ultrasonic impact treatment (UIT) is known as a promising surface modification process for industrial practice to manufacture components with high anti-fatigue performance, on which a compressive residual stress layer can be introduced up to a typical depth of hundreds micrometers. In this study, combined properties of wear and corrosion resistance for AISI 304 austenitic stainless steel components is primarily concerned and achieved by employing an ultrasonic impact treatment process. Surface integrity of UIT processed AISI 304 austenitic stainless steel components can be effectively improved by controlling the surface integrity parameters including surface features and surface characteristics achievable with respect to the desired functional performance. The wear resistance of UIT processed stainless steel components is notably improved, with a corrosion resistance comparable to that of original ones even though austenite-to-martensite phase transformation is observed. The multiple surface integrity parameters of both surface features and surface characteristics simultaneously achieved by the surface modification, exhibiting strong interactions between them, are responsible for the high performance of components with combined properties.

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Keywords: Surface integrity; Surface modification; Ultrasonic impact treatment; Surface feature; Surface characteristic; High performance manufacturing

1. Introduction

The surface integrity, defined as the inherent or enhanced condition of a surface produced by machining processes or other surface generation operations, was firstly born from machining process where compressive residual stress on machined components surface was found to be a determining factor to enhance fatigue life of the components [1,2]. Up to date, it has been proved that surface integrity involves numerous surface integrity parameters having a profound influence on component performance, and the surface integrity parameters concerned include such as hardness, depth of plastic deformation layer, microstructure and the associated residual stresses in a variety of machining operations such as turning, milling, grinding, electrical discharge machining etc. [3-5]. Therefore, the influence of various surface integrity parameters on the final performance could be understood in advance and then it is possible to design a surface integrity meeting the demand of high performance components. Moreover, conventional materials removal manufacturing alone is not capable for manufacturing a component with high performance of combined properties since a high surface integrity of is frequently restricted by the geometrical, physical and chemical constraints from the component design and its base materials [6]. For example, in the case of surface white layer formation on machined steel and superalloy components during removal machining processes including hard turning, drilling, grinding, milling, and electrical discharge machining etc., as a result of strong plastic deformation accompanied with notable thermal effects, where the surface white layer has a higher hardness than that of base materials, but usually leads to a lower fatigue performance [7,8].

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In this work, a surface modification technique, ultrasonic impact treatment (UIT), is alternatively employed to explore influence of multiple surface integrity parameters in a controllable way on the high performance of austenitic stainless steel AISI 304 components with combined wear and corrosion resistance, by which a new surface layer on the base material with desired multiple surface integrity parameters is obtained otherwise unattainable in conventional materials removal manufacturing. Surface integrity parameters are divided into two categories in relation to the final performance of components, i.e. surface features and surface characteristics, where the former includes the features of topography and chemical composition, grain morphology, and phase structure etc. in the surface layer created by the surface modification, and the latter includes the physical and chemical properties associated with the new surface layer, such as microhardness and residual stress etc. It is demonstrated that the surface integrity parameters controllably achieved by surface modification presented strong interactions, leading to an improved component performance of combined wear and corrosion properties.

2. Experimental

The UIT was conducted for AISI 304 austenitic stainless steel disc samples with a dimension of Φ100×5 mm after solid solution treatment on a HJ-III ultrasonic impact device with an improved ultrasonic impact head configuration. For the treatment, the output of ultrasonic generator at a central frequency of 17.8 kHz generate a 30 μm vibration amplitude of ultrasonic horn to drive the impact head containing 19 cylindrical pins with a diameter of 2 mm and length of 25 mm. The impact head was sequentially shifted with a raster-scan mode at a variable speed along the raster lines in parallel spaced by 0.25 mm, till the whole desirable surface area was treated. By adjusting the shift speed the different impact intensity of UIT is set as 3, 6 and 24 min/cm^2, respectively.

For analysis of surface features and characteristic on UIT processed AISI 304 austenitic stainless steel, the disc samples were sectioned into block samples with a dimension of 20 × 20 × 5 mm^3 by wire electrical discharge cutting. Surface roughness, phase composition and metallurgical feature were analyzed by using surface profilometer, X-ray diffractometer and optical microscope, respectively. Microhardness and residual stresses along the depth of surface layer were measured correspondingly using Vickers indenter and X-ray diffraction technique based on sin2ψ-method for both registered diffraction peaks from austenite (211) and martensite (311).

Wear performance of UIT processed AISI 304 austenitic stainless steel was conducted on a ball-on-disk WTM-2E tribometer under dry sliding conditions, against a 4 mm diameter Si_3N_4 ceramic ball under a normal load of 400 g. The wear track profiles wear measured to estimate the wear loss, after a test time of 1 h with rotating speed of 300 rpm of ceramic ball on a circle of 7-mm diameter. Corrosion resistance of samples was evaluated by electrochemical polarization curves measurement in boric acid aqueous solution prepared from analytical grade agent of 9.15 g boric acid (H_3BO_3), 14.2 g borax ($Na_2B_4O_7$) and 1000 ml deionized water, where a conventional three-electrode cell was used and monitored on an EG&G PAR model 2273 potentiostat/galvanostat interfaced with a computer.

3. Surface features

Surface roughness (Ra and Rz) was measured for UIT treated AISI 304 samples under the different impact intensity of 3 min/cm^2, 6 min/cm^2, and 24 min/cm^2, respectively, as listed in Table 1. The original samples have a highest roughness due to machining by wire electrical discharge. It is clearly seen that the UIT treatment produce a much smother surface from original Ra of 4.04 μm and Rz of 25.7 μm correspondingly down to a value of 0.5-0.6 μm and 3-4 μm. Moreover, it seems that an optimal value could be found for moderate impact intensity of 6 min/cm^2 with smoothest surface feature.

Table 1 Surface roughness of UIT processed AISI 304 stainless steels.

Impact intensity	R_a (μm)	R_z (μm)
0 min/cm^2 (original)	4.04	25.7
3 min/cm^2	0.618	3.31
6 min/cm^2	0.551	3.46
24 min/cm^2	0.578	4.4

Based on XRD measurement, phase transformation from γ to α′-martensite is confirmed in the surface layer for all the UIT processed samples at the different impact intensity. No ε-martensite phase was detected, different from the result of previous investigations [9,10]. It is implied that, the deformation mode of 304 austenitic stainless steel under UIT processing follows the sequence of phase transformation γ → mechanical twin (γ′) → α′-martensite, rather than that of γ → ε-martensite → α′-martensite [11]. The formation of twins and ε-martensite during plastic deformation strongly depends on stacking fault energy (SFE) and deformation temperature. It was also showed that the presence of ε-martensite only found in steels with SFE < 13 mJ/m^2 [10]. The high SFE of material and the heat generated during impact may contribute to suppression of ε-martensite formation. Subsequently, the volume fraction of α′-martensite ($V_{\alpha'}$) can be evaluated using eq. (1),

$$V_\alpha = \frac{\frac{1}{n}\sum_{j=1}^{n}\frac{I_\alpha^j}{R_\alpha^j}}{\frac{1}{n}\sum_{j=1}^{n}\frac{I_\gamma^j}{R_\gamma^j}+\frac{1}{n}\sum_{j=1}^{n}\frac{I_\alpha^j}{R_\alpha^j}} \quad (1)$$

where n, I and R are the number of peaks for the calculated phase, the integrated intensity of the diffraction peaks and the material scattering factor, respectively. The α′-martensite (211) peak and the γ-austenite (311) peak are counted for calculating the volume fraction of α′-martensite. The estimated volume fraction of α′-martensite in the surface layer of UIT processed AISI 304 are listed in Table 2.

Table 2 The volume fraction of α′-martensite in the surface layer of UIT processed AISI 304 stainless steels.

Impact intensity	$V_{\alpha'}$ (%)
3 min/cm^2	82.6
6 min/cm^2	95.8
24 min/cm^2	100

It is shown that the higher the impact intensity, the higher the content of deformation-induced martensite phase produced in the surface layer, i.e. 82.6%, 95.8 and 100% $V_{\alpha'}$ for 3, 6 and 24 min/cm^2 UIT treated samples, respectively. The efficiency of phase transformation is relatively higher as compared to that of shot peening, i.e. an improved high-energy shot peening that led to a maximum content of 91% martensite phase with increasing the treatment time up to 15 min followed by a decrease with a further increased treatment time [12]. Other surface plastic deformation methods such as deep rolling hardly resulted in such a high content of martensite [13], with usually 20-40% α′-martensite generated.

Fig. 1 shows optical micrographs of the cross-sectional areas of UIT processed samples at the different impact intensity. The original microstructure of AISI 304 stainless steel contains γ-austenite with a few twins visible. Both grain refinement and microtwin formation are confirmed in the plastically deformed surface layer after the UIT processing, where a tendency of deeper deformation to a depth of 300-400 µm is clearly obtained as increasing the impact intensity from 3 to 24 min/cm^2, and the increasing tendency seems to slow down as a similar metallographic feature is observed for 6 and 24 min/cm^2. Note that, significant grain refinement in the top surface layer was produced at the higher impact intensity above 3 min/cm^2, and the moderate impact intensity at 6 min/cm^2 leads to a more uniform grain size distribution and random grain orientation in the surface layer.

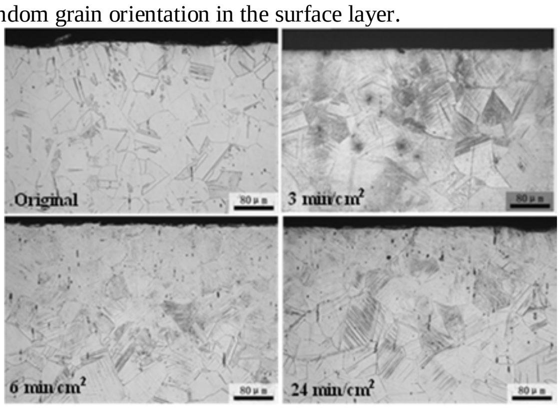

Fig. 1. Optical micrographs of the cross-sections of original and UIT samples.

4. Surface characteristics

Fig. 2 shows the microhardness profile of the samples at different impact intensity, respectively. Similar profiles of hardening is found for all the UIT processed samples, with a maximal hardness of about 4500 MPa at the top surface, about 2 times of 2000-2500 MPa for original sample. The profile indicates a hardening layer is extended to about 400-500 µm. The increase in hardness is mainly attributed to the phase transformation, grain refining and microtwins formation under the plastic deformation. In addition, residual stress could also affect to some extent the microhardness.

The residual stress profiles are presented in Fig. 3. The (M) and (A) represents the data of residual stress measurement from martensite and austenite phase respectively, since the martensite phase become the major phase in the top surface layer after UIT processing. All UIT processed samples shows a similar compressive residual stress distribution down to a depth of about 1000 µm with a maximum magnitude about -800 MPa. Plastic deformation and phase transformation contribute to the residual stress formation. The maximum compressive residual stress is not proportional to the increase of impact intensity, indicating a saturated tendency after a certain impact intensity, similar to the result reported previously [14], even possibly with a slight decrease of the maximum compressive residual stress in the surface layer under increased impact intensity.

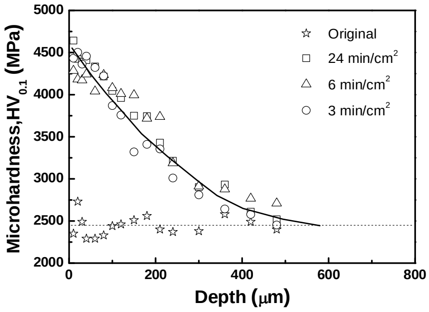

Fig. 2. Vickers micro hardness depth profiles of original and UIT samples.

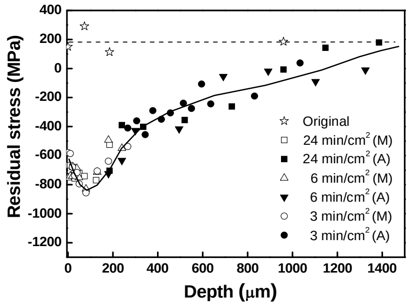

Fig. 3. Residual stress depth profiles of original and UIT samples.

5. Influence of multiple surface parameters on performance

Fig. 4 shows typical cross-sectional profiles of wear tracks for the original and UIT samples. For the original sample, the wear tracks was about 10 µm deep and 730 µm wide with apparent pileup due to plastic ploughing by the wear pair of Si_3N_4 ball. For the UIT samples, wear tracks are much smaller in depth and width expect for the case of 24 min/cm^2, and a minimum value is found under 6 min/cm^2. In this case, a single phase layer of martensite is produced under 24 min/cm^2 with slightly higher hardness as compared to the other two impact intensities. Under the strong plastic deformation in the steel due to contact between the wear pairs, the lower toughness of the surface layer may promote surface fracture and fragmentation with debris formation, and subsequently the harder phase debris may further enhance the wear rate.

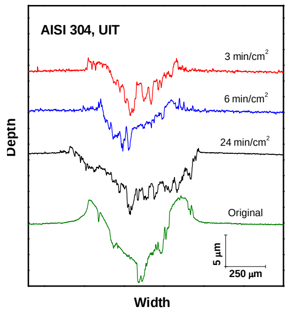

Fig. 4. Cross-sectional profiles of wear tracks on original and UIT samples.

Fig. 5 shows the cyclic potentiodynamic polarization curves in boric acid aqueous solutions for the original and UIT samples. All the samples present a transition from self-passivation to transpassivation process, with similar curve shape but with different corrosion potential and passive current. The corrosion potentials of UIT samples with the impact intensity of 3, 6 and 24 min/cm^2 are -238, -228 and -149 mV respectively, slightly higher than that of -251 mV for original sample. However, the passive currents of the UIT samples are also slightly higher than that of original sample. Among the UIT processed samples, that of 6 min/cm^2 displays the smallest corrosion current close to the original AISI 304 stainless steel. Even though the martensite phase commonly has a lower corrosion resistance than austenite phase, the UIT processed samples at the impact intensity of 6 min/cm^2 present a comparable corrosion resistance. It is shown that, all the UIT processed samples have a similar distribution of microhardness and residual stress, but different phase composition, grain morphology/orientation and surface roughness, leading to different wear and corrosion performance. Surface features and surface characteristics with strong interactions by UIT processing lead to the combined wear and corrosion resistance.

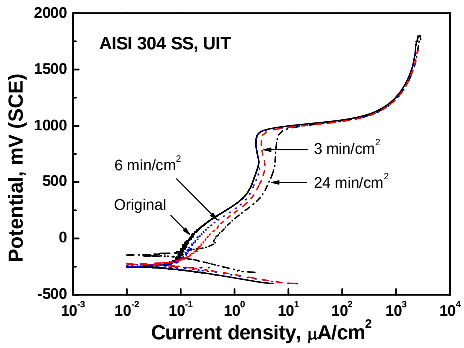

Fig. 5. Cyclic potentiodynamic polarization curves in boric acid aqueous solutions for the original and UIT samples, respectively.

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